TP 14309E

PERFORMANCE MEASURES FROM TRACK GEOMETRY CARS:
A Dynamic Response L/V Predictor

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Kingston, ON K7M 6B4

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Performance Measures from Track Geometry Cars:

A Dynamic Response L/V Predictor

by

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Note on the units used in this report
Because the established practice within the North American railway industry uses imperial units for the basic measures of distance, speed and track geometry measurements, imperial units are used for those measures in this report. For speed and measurement intervals, which occur frequently throughout the report, equivalent metric units are not shown since they would detract from the flow of the text. A table of metric conversions for the units involved is presented below.

In the area of dynamic modelling of vehicle response, the use of metric units is standard practice; therefore, metric units are used for this in the report, with imperial equivalents shown where measures such as car weight are involved.

Conversion Factors	
Imperial Unit	Equivalent Metric Unit
1 in.	25.4 mm
1 ft.	0.3048 m
1 mi.	1.6093 km
1 ton	0.907 t
1 lb.	0.4536 kg (mass) 4.45 N (force)
degree curvature	Radius (m) = $\frac{1,746.375}{\text{degrees-curvature}}$

Un sommaire français se trouve avant la table des matières.

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16. Abstract

This report presents the results of the second phase of a test and analysis program aimed at developing better performance indicators for track geometry. The test program involved the instrumentation of two freight cars to record events of undesirable lateral/vertical (L/V) force ratios and the associated track geometry at those locations. The analytic program involved the development of a predictor software program that can be run on board the geometry car to predict where the occurrences of undesirable L/V will occur. The predictor performed well in isolating track conditions that will produce high L/Vs.

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16. Résumé

Le rapport présente les résultats de la deuxième phase d'un programme d'essai et d'analyse dont le but est d'améliorer les indicateurs de performance de la géométrie de la voie. Le programme d'essai a consisté à instrumenter deux wagons de marchandises pour enregistrer les cas de rapport de forces latérales/verticales (L/V) indésirable, et la géométrie de la voie à ces endroits. Le programme d'analyse a comporté le développement d'un logiciel de prédiction qui, chargé à bord du wagon d'analyse, peut prévoir où se présenteront des rapports L/V indésirables. Le logiciel a affiché de bons résultats dans la reconnaissance des tronçons de voie associés à des rapports L/V élevés.

17. Mots clés Mesures de performance, géométrie de la voie, dynamique des véhicules, chevauchement du rail, risque de déraillement, planification de l'entretien, rapport de forces latérales/verticales, logiciel de prédiction du rapport L/V	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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Executive Summary

In the second phase of a test and analysis program to develop better performance indicators for track geometry, instrumentation and data acquisition systems were developed to collect geometry and test-car dynamic wheel force data. Vertical spring-nest displacements were also measured for the four suspensions of two test cars. A loaded and an empty hopper car, which had been identified as cars with a higher derailment risk from geometry conditions, were instrumented and transported across a range of track classes on Canadian Pacific Railway's rail network, coupled with the railway's track geometry car. The geometry cars provided speed, curvature, location and the geometric conditions that the test cars were traversing.

The first phase of the program identified locations of high dynamic action based on wheel unloading. While vehicle dynamic action and suspension unloading are necessary ingredients for geometry-related derailments, the present phase of research has markedly reduced the number of 'undesirable' response sites by focusing on those that produce high lateral/vertical (L/V) wheel forces that are associated with wheel climb derailment risk.

The L/V predictor that has been developed has the capability to process geometry data in real time and predict locations that will produce high L/V ratios for several cars at multiple speeds and in both running directions.

There is still work to be done to better understand the appropriate thresholds to select as indicators of an elevated risk of derailment and to define the best corrective measures to take at identified sites.

Sommaire

Au cours de la deuxième phase d’un programme d’essai et d’analyse visant à améliorer les indicateurs de performance de la géométrie de la voie, des instruments et des systèmes d’acquisition de données ont été développés pour colliger des données sur la géométrie de la voie et les forces dynamiques exercées par les roues de wagons d’essai. Le mouvement vertical des blocs-ressorts des quatre suspensions de deux wagons d’essai a également été mesuré. Un wagon-trémie chargé et un wagon-trémie vide, reconnus pour présenter des risques élevés de déraillement en cas de défaut de géométrie de la voie, ont été instrumentés et transportés sur diverses voies de catégories différentes du réseau du Canadien Pacifique, accouplés au wagon d’analyse de la société ferroviaire. En plus des données sur la géométrie de la voie dans les zones traversées, le wagon d’analyse colligeait des données sur la vitesse, la courbure de la voie et l’emplacement.

La première phase du programme avait permis de déterminer les endroits où se déclenchait une forte action dynamique, mesurée par la perte de contact roue-rails. Bien que l’action dynamique des véhicules et les pertes de contact roue-rails soient des ingrédients nécessaires des déraillements dus à la géométrie de la voie, la présente phase de la recherche a repéré beaucoup moins de sites susceptibles de déclencher des réactions «indésirables», en se concentrant sur ceux où les rapports élevés de forces latérales/verticales (L/V) exercées par les roues sont associés à un risque de déraillement par chevauchement du rail.

Le logiciel de prédiction du rapport L/V développé en marge des présents travaux peut traiter les données de géométrie en temps réel et prévoir les endroits qui produiront des rapports L/V élevés pour plusieurs wagons, à plusieurs vitesses et dans les deux sens de marche.

Il est recommandé de poursuivre les travaux afin de déterminer les seuils à choisir en tant qu’indicateurs d’un risque élevé de déraillement et de définir les meilleures mesures correctives à prendre aux sites identifiés comme dangereux.

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Glossary of Acronyms

AAR	Association of American Railroads
CN	Canadian National Railway
CPR	Canadian Pacific Railway
FRA	Federal Railroad Administration
IWS	instrumented wheel set
Kips	1,000 pounds
LT-F	lead truck forward direction
LT-R	lead truck reverse direction
L/V	lateral-to-vertical
MCO	mid-chord offset
Mtn.	mountain
NRC	National Research Council Canada
Pr.	prairie
TEC	track evaluation car
TT-F	trailing truck forward direction
TT-R	trailing truck reverse direction

1 INTRODUCTION

1.1 Background

The principal means deployed by all major railways in measuring the geometric quality of track is a track geometry car or track evaluation vehicle. While these vehicles have the capability of measuring track parameters of interest, the interpretation of the measurements in assessing track condition and in deciding what to do about it varies widely and is in continuous evolution.

Most railways process their track geometry measurements on a short-segment basis in an effort to assess the overall level of quality. The processing provides a Track Quality Index, which is then used to trigger maintenance action at specified thresholds. The variances (or standard deviations) of geometry deviations are indices used by many railways as surrogates for quality. Variance provides a valid indication of track geometry "roughness"; however, it has limitations as a performance measure, the principal one being that vehicle dynamic response is very dependent on the wavelength of track deviation stimuli. Thus, a relatively smooth track segment at a critical wavelength may produce a more violent vehicle response than a rougher segment at a different wavelength.

Regulatory defects (or exceptions) are also derived from the track evaluation cars. These are local geometric conditions with thresholds—defined within the Canadian Track Standard Regulations—that trigger immediate slow orders until maintenance action is taken. Defect definitions have evolved on a historic basis of judgement and derailment experience. The uncertainty in their effectiveness is highlighted by the Canadian railways' experience of significant increase in defect count on well-performing track when they incorporated U.S. Federal Railroad Administration (FRA) track standards into their own standards in 1992 [Roney, 1993].

A key factor in the present track geometry regulations is that they focus largely on single track perturbations and involve a measurement system that is forced to meet physical verification via measurement of mid-chord offset (MCO) from a 62 ft. chord. Track-vehicle dynamic interaction is speed dependent and can be influenced more by a series of small deviations at a critical wavelength than a single large perturbation. This has been known to the industry for some time and the authors of this report have been involved in a number of test/development programs addressing the issue.

1.2 Previous Phase

The present study follows a previous phase of research in which low-cost instrumentation and broad coverage of the Canadian track network were used to identify the frequency of occurrence of undesirable vehicle response [TranSys Research, 2002]. Two car types (empty hopper and empty tank) were instrumented at the suspension points and traversed the railway networks of CN and CPR in a train consist with their track geometry cars over a 12 month period. “Bad-spot” predictor software was developed and has been successful in identifying locations of high dynamic action. The predictor model outperformed the existing regulatory definitions of “bad track” as a predictor of freight car suspension unloading. On track Classes 3 and 4, the number of defects identified was below the number of priority exceptions/defects reported by existing standards. For the initial definition of “undesirable” the number of occurrences for both cars, but especially the lighter hopper car, on Class 2 track was too high to be economically applied as a “corrective-action-required” indicator.

The present phase of research involved field tests with an instrumented wheelset in order to assess the lateral and vertical wheel forces in addition to the suspension forces. A test route was selected to include Class 2 subdivisions that were found in the previous phase to produce a large number of unloading hits and a number of Class 4 mountain subdivisions with curvature up to 11 degrees.[1]

1.3 Objective

The objective of this project is to reduce train derailments, including some termed “unexplained”, by identifying track locations that stimulate high lateral/vertical wheel force ratios for a specified car type.

1.4 Report Layout and Content of Subsequent Chapters

The balance of this report is divided into five chapters. In Chapter 2 we describe the instrumentation, data collection activity and criteria for denoting undesirable levels of vehicle response.

In Chapter 3 we describe the development of predictor software for on-board processing of track geometry data.

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[1] Track classes are a regulatory term used to describe the tighter tolerances required for track geometry at increasing speeds. The maximum freight train speeds allowed on Class 1 through Class 5 tracks are 10 mph, 25 mph, 40 mph, 60 mph and 80 mph, respectively.

In Chapter 4 we assess the performance of the predictor in isolating the measured locations of high L/V ratios.

In Chapter 5 we test the predictor at a derailment site at which geometry might have been a contributing factor.

Finally, in Chapter 6 we present our conclusions and recommendations.

2 TEST CARS AND DATA ACQUISITION

In this chapter we describe the freight cars that were selected for testing and the instrumentation installed on each test car.

2.1 Instrumented Test Cars

An instrumented wheelset test program was undertaken to collect detailed wheel force data for use in further developing the capabilities of the track performance predictor program. This work involved installation of various test instrumentation on two covered hopper cars, one empty and one loaded, which were used to measure wheel forces, secondary suspension displacements and car body motions in real time. Data were collected while traversing CPR main-line track, starting at Saskatoon, Saskatchewan, on April 30, 2003, and ending in Kamloops, British Columbia, on May 6, 2003. National Research Council Canada (NRC) was subcontracted to provide and install all instrumentation on the test vehicles and perform the data acquisition for these tests.

The instrumented wheelset test consist comprised a loaded hopper car (CP 388601), an empty hopper car (CP 388687) and an instrumentation car (CP 66). These cars were inserted between a locomotive and the standard CP track evaluation consist comprising the TEC box car (CP 424994), the TEC accommodation car (CP 65) and the CP Track Evaluation Car (CP 64). This instrumented wheelset testing was conducted in conjunction with CPR's regularly scheduled track geometry test program.

The loaded hopper car (CP 388601) was carrying a load of potash with a nominal gross vehicle weight of 268,000 lb. Measurements of the load height below the hatch openings in the roof were taken and are summarized in Figure 1. It is reasonable to infer from these measurements that the centre of gravity of the loaded hopper car was low.

The instrumentation used for these tests consisted of two instrumented wheelsets (IWS), four accelerometers, two gyros, eight displacement transducers and a Q-Tron used to calculate speed and track distance. All instrumentation signals were sampled at a rate of 150 Hz, after first being passed through a 20 Hz low-pass filter, using a Megadac 5414AC/DC system equipped with a 16 bit analogue-to-digital converter. Model 682SH-1 amplifier cards were used for signal conditioning to provide gain and 8-pole low-pass Butterworth filtering with a 64 dB per octave roll-off rate. All instrumentation was installed by NRC personnel at the CPR facility in Saskatoon, Saskatchewan, on April 24, 25, 28 and 29, 2003.

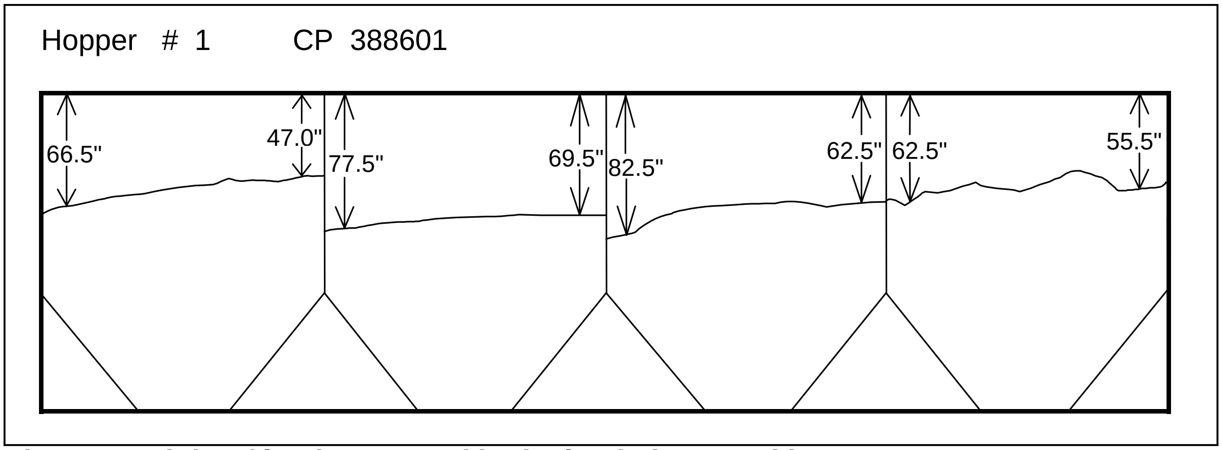

Figure 1 Height of load measured in the loaded covered hopper car

Each hopper car was instrumented with one instrumented wheelset, four displacement transducers, two accelerometers and one roll gyro. Figure 2 depicts where each instrument was installed in the test consist. The instrumented wheelsets were installed in the leading axle position of the rear truck of the loaded hopper car (axle 3 in Figure 2) and in the leading axle position of the leading truck of the empty hopper car (axle 5 in Figure 2). The photograph in Figure 3 shows the trailing end (A-end) of the loaded hopper car after all instrumentation had been installed.

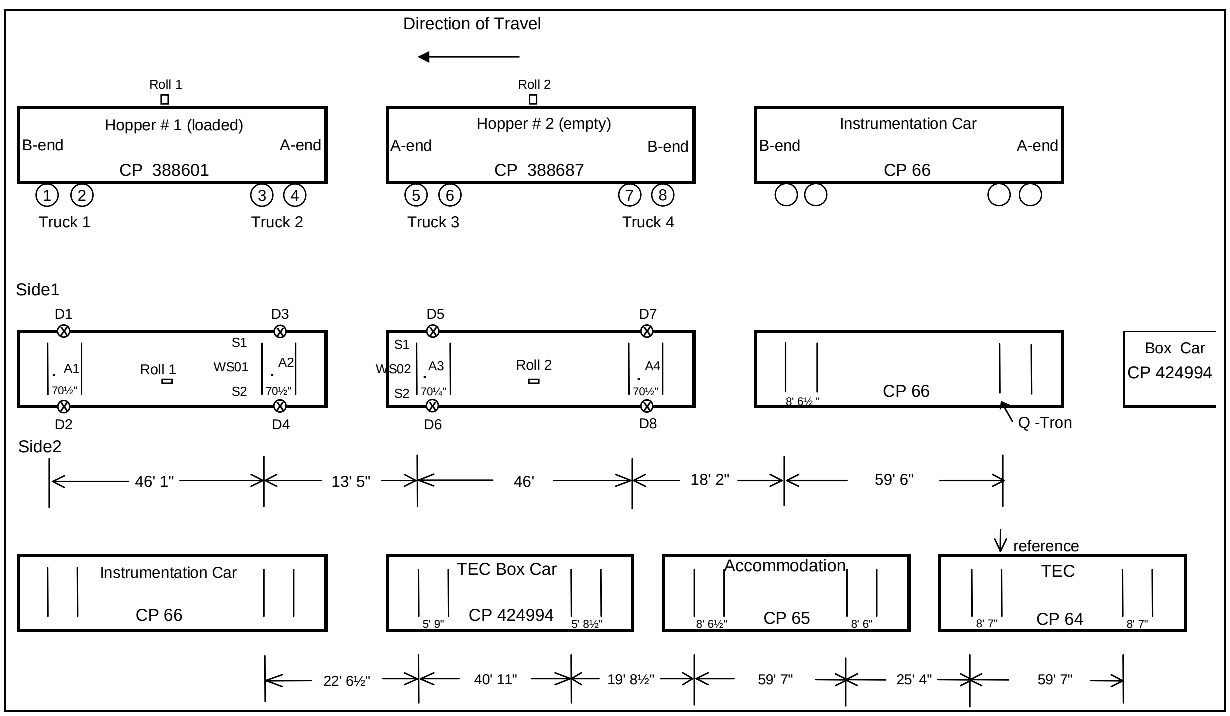

Figure 2 Location of instrumentation installation

The instrumented wheelsets furnished by NRC and used in these tests were 36-inch diameter and rated for 100-ton axle loads. They are capable of continuously measuring the force and moments acting at the wheel/rail contact patch of each wheel in three dimensions. The supporting electronics resolved measurements into the vertical, lateral and longitudinal forces acting on each wheel in real time and calculated the ratio of lateral-to-vertical forces (L/V).

Figure 3 Trailing end of loaded hopper car with instrumentation installed

Figure 4 is a photograph of one of the instrumented wheelsets being installed in the truck of one of the covered hopper cars. Figure 5 shows a close-up view of the slip ring assembly and cable harness required to transmit the measurement signals from the rotating axle to electronic interface and data collection equipment remotely located in the instrumentation car (CP 66).

Displacement transducers were installed to measure movement across all secondary suspensions of both the loaded and empty covered hopper cars. String potentiometers were used for this test and installed as depicted in Figure 6.

Figure 4 Instrumented wheelset during installation

Measurements from these transducers indicate the relative motion between the truck bolster and side frame and may be used to infer the magnitude of the vertical suspension force being generated. Single axis accelerometers were installed on the body of each covered hopper to measure the vertical acceleration near each truck bolster. The measurements provide a means to identify and differentiate pitch and bounce motions of the car body. A gyro was also installed on top of each covered hopper car halfway along its length to measure the roll motion of the car body. The complete instrumentation package installed on each hopper car is sufficient to determine the gross car body motion.

A total of 39 signals, as summarized in Table 1, were digitized and stored in binary format on optical storage media using the Megadac 5414AC/DC system. In order to keep the data files to a manageable size, the real-time instrumented wheelset and car response data collected on a track subdivision were stored in a sequence of files, each of which would typically correspond with about 10 miles of travel. There were short gaps in the data collection due to the time required to close one output file and open a new one; however, the Q-Tron continued to accurately track distance during these intervals.

Figure 5 Instrumented wheelset installed in truck

Figure 6 Details of displacement transducers

Table 1 Instrumentation signals collected during the instrumented wheelset test

Signal Name	Installation Location	Orientation / Description	Unit of Measurement
Y1	Loaded Hopper, Wheelset 3, Side 1	Lateral Force	Kips
Q1	Loaded Hopper, Wheelset 3, Side 1	Vertical Force	Kips
Y2	Loaded Hopper, Wheelset 3, Side 2	Lateral Force	Kips
Q2	Loaded Hopper, Wheelset 3, Side 2	Vertical Force	Kips
TX1	Loaded Hopper, Wheelset 3, Side 1	Longitudinal Force	Kips
TX2	Loaded Hopper, Wheelset 3, Side 2	Longitudinal Force	Kips
Y3	Empty Hopper, Wheelset 5, Side 1	Lateral Force	Kips
Q3	Empty Hopper, Wheelset 5, Side 1	Vertical Force	Kips
Y4	Empty Hopper, Wheelset 5, Side 2	Lateral Force	Kips
Q4	Empty Hopper, Wheelset 5, Side 2	Vertical Force	Kips
TX3	Empty Hopper, Wheelset 5, Side 1	Longitudinal Force	Kips
TX4	Empty Hopper, Wheelset 5, Side 2	Longitudinal Force	Kips
D1	Loaded Hopper, Truck 1, Side 1	Spring Nest Deflection	Inch
D2	Loaded Hopper, Truck 1, Side 2	Spring Nest Deflection	Inch
D3	Loaded Hopper, Truck 2, Side 1	Spring Nest Deflection	Inch
D4	Loaded Hopper, Truck 2, Side 2	Spring Nest Deflection	Inch
D5	Empty Hopper, Truck 3, Side 1	Spring Nest Deflection	Inch
D6	Empty Hopper, Truck 3, Side 2	Spring Nest Deflection	Inch
D7	Empty Hopper, Truck 4, Side 1	Spring Nest Deflection	Inch
D8	Empty Hopper, Truck 4, Side 2	Spring Nest Deflection	Inch
A1	Loaded Hopper, Front	Vertical Acceleration	G
A2	Loaded Hopper, Back	Vertical Acceleration	G
A3	Empty Hopper, Front	Vertical Acceleration	G
A4	Empty Hopper, Back	Vertical Acceleration	G
ROLL1	Loaded Hopper, Centre	Car Body Roll	Degree
ROLL2	Empty Hopper, Centre	Car Body Roll	Degree
SPEED1	Speed Calculated from Car 66		Mph
SPEED	Speed Calculated from Q-Tron Pulses		Mph
LONV1	Loaded Hopper, Wheelset 3, Side 1	Lat/Vert Wheelset 3 – Side 1	Non-dimensional
LONV2	Loaded Hopper, Wheelset 3, Side 2	Lat/Vert Wheelset 3 – Side 2	Non-dimensional
LONV3	Empty Hopper, Wheelset 5, Side 1	Lat/Vert Wheelset 5 – Side 1	Non-dimensional
LONV4	Empty Hopper, Wheelset 5, Side 1	Lat/Vert Wheelset 5 – Side 2	Non-dimensional
AXLE1	Loaded Hopper, Wheelset 3	SUM L/V Wheelset 3	Non-dimensional
AXLE2	Empty Hopper, Wheelset 5	SUM L/V Wheelset 5	Non-dimensional
T950	Pulses from Q-Tron	240 pulses per revolution	Pulses
T951	Pulses from Q-Tron	1 pulse per 273 revolutions	Pulses
MP1	Pulses from Car 66	4 pulses per revolution	Volts
DIST	Calculated Distance from Q-Ton Signal	Distance in miles	Miles
MSTAMP	Manual Event Marker	Manual Event Marker	Volts

2.1.1 CPR TEC Consist

Because of technical limitations restricting the interface to the TEC car's on-board computers, it was not possible to gain real-time access to the track geometry signals. Rather, the complete track geometry, as indicated in Table 2, was supplied (in the form of a special "one-foot" file) from the TEC computer at the end of a test.

Table 2 Geometry data acquired on the test subdivisions

Channel	Signal Description
0	Track left rail vertical profile
1	Track right rail vertical profile
2	Left rail alignment
3	Right rail alignment
4	Track gauge
5	Track superelevation
6	Track curvature
7	Test train speed

The time-based binary instrumented wheelset data files were post-processed using a purpose-built program to extract desired portions of the data to ASCII format. Another post-processing program was used to extract the corresponding track geometry in one-foot intervals from the distance-based binary files obtained from CPR Track Evaluation Car 64. Although a distance signal was incorporated within the instrumented wheelset data, fine alignment of the time-based data with the distance-based track geometry data was achieved by shifting the data so that the observed wheel lateral force development properly coincided with spirals and curves within the recorded track geometry. The mileage recorded in the track geometry files is periodically adjusted, typically at the start of a new mile, and shows up as a positive or negative step in the position reported. Re-alignment of the time-based data with the distance-based track geometry was required at each such location.

2.1.2 Track Network Coverage

Approximately 940 mi. of CPR track were traversed during this testing—around 600 mi. of which were in prairie and foothills, and the remainder were in mountainous territory. Table 3 summarizes the subdivisions in the order in which they were tested. Also listed in this table is the number of miles for which good instrumented wheelset and car response data were successfully obtained for each of these track subdivisions. Approximately 40 percent coverage was obtained for the loaded hopper car and 63 percent for the empty hopper car. The primary cause of missing data was loosening slip rings on the instrumented wheelsets. Since these tests were being conducted in conjunction with regular CPR track geometry testing it was not always possible to stop the train and effect immediate repairs. There was also a failure in the instrumented wheelset interface electronics, which occurred on the third day of testing and was repaired during a scheduled stopover in Calgary.

Table 3 CPR subdivisions traversed during the instrumented wheelset testing

CPR Subdivision	Date Tested	Geometry File Miles	Valid Loaded Car Miles	Valid Empty Car Miles
Wilkie	April 30, 2003	100	72	100
Hardisty	May 1, 2003	131	10	97
Wetaskiwin	May 1, 2003	95	84	93
Scotford	May 2, 2003	35	0	0
Leduc	May 2, 2003	91	0	3
Red Deer	May 2, 2003	95	78	0
Laggan	May 5, 2003	137	9	110
Mountain	May 5, 2003	126	0	60
Shuswap	May 6, 2003	128	124	124
Total		938	377	587

3 REAL-TIME L/V PREDICTOR SOFTWARE

3.1 Vehicle Model

The vertical response model that was developed in phase 1 was enhanced to provide lateral response and force prediction. The rail vehicle model uses the same 11 rigid bodies and 22 connection elements that were described in the phase 1 report [TranSys Research, 2002]. The rigid bodies include four axles, four truck side frames, two truck bolsters and a car body. To model the lateral forces, the degrees of freedom were expanded from 35 in the original model to 48 in the new model. Since the model is not a time domain simulation, there is no processing time cost associated with the additional degrees of freedom. However, the derivation of lateral forces does increase the run times in comparison with the phase 1 vertical response model. It is still capable of simulating multiple vehicles at multiple speeds in real time.

3.2 L/V Force Predictor Program

The upgraded model still uses a Fourier Transform of the track geometry for harmonic response and then applies other parameters for non-harmonic response variables over a 150-ft. window. It advances forward in 50-ft. increments. The measured data indicate that it is possible to generate very high levels of vertical and lateral force variations at the same location without developing a high L/V ratio. The phase relationship between them is such that the wheelset seldom experiences high L/V ratios. The model was further enhanced with an extra routine that assesses the phase relationship of the lateral and vertical forces. The model now assesses the lateral and vertical forces at one-foot intervals within each 150-ft. window. Figure 7 compares the model predictions with the data at one of the worst hit sites from the field tests. Vertical arrows indicate the predicted and the actual hit locations. Even though the L/V force ratio occurs at a very short section of track, the geometry condition that creates the high L/V occurs over a section of track that exceeds the truck centre spacing of the car. Thus, a minimum 150-ft. window is still the relevant segment length for corrective action. The model's final output is based on the L/V derived for the complete window and accumulated adjacent windows if multiple L/Vs are predicted. For the segment shown in Figure 7, the complete 300-ft. track segment illustrated is designated by the model as a priority level hit.

3.2.1 All Axles, Both Directions, Multiple Speeds

The importance of the phase relationship between lateral and vertical forces also means that the same section of track will produce different results for different directions of travel. Thus, the model separately assesses the lead axles of the front and rear trucks for forward direction travel (axles 1 and 3) and reassesses the vertical and lateral forces for the lead axles if the car were travelling in the reverse direction (axles 2 and 4).

The program assesses these forces at the critical vehicle speed and at the track class speed limits up to the posted speed limit for the track segment. Thus, if the speed limit is 60 mph, the hopper car's force response would be assessed for speeds of 25 mph, 40 mph and 60 mph. If the speed limit is 35 mph, the force response is calculated for speeds of 25 mph and 35 mph.

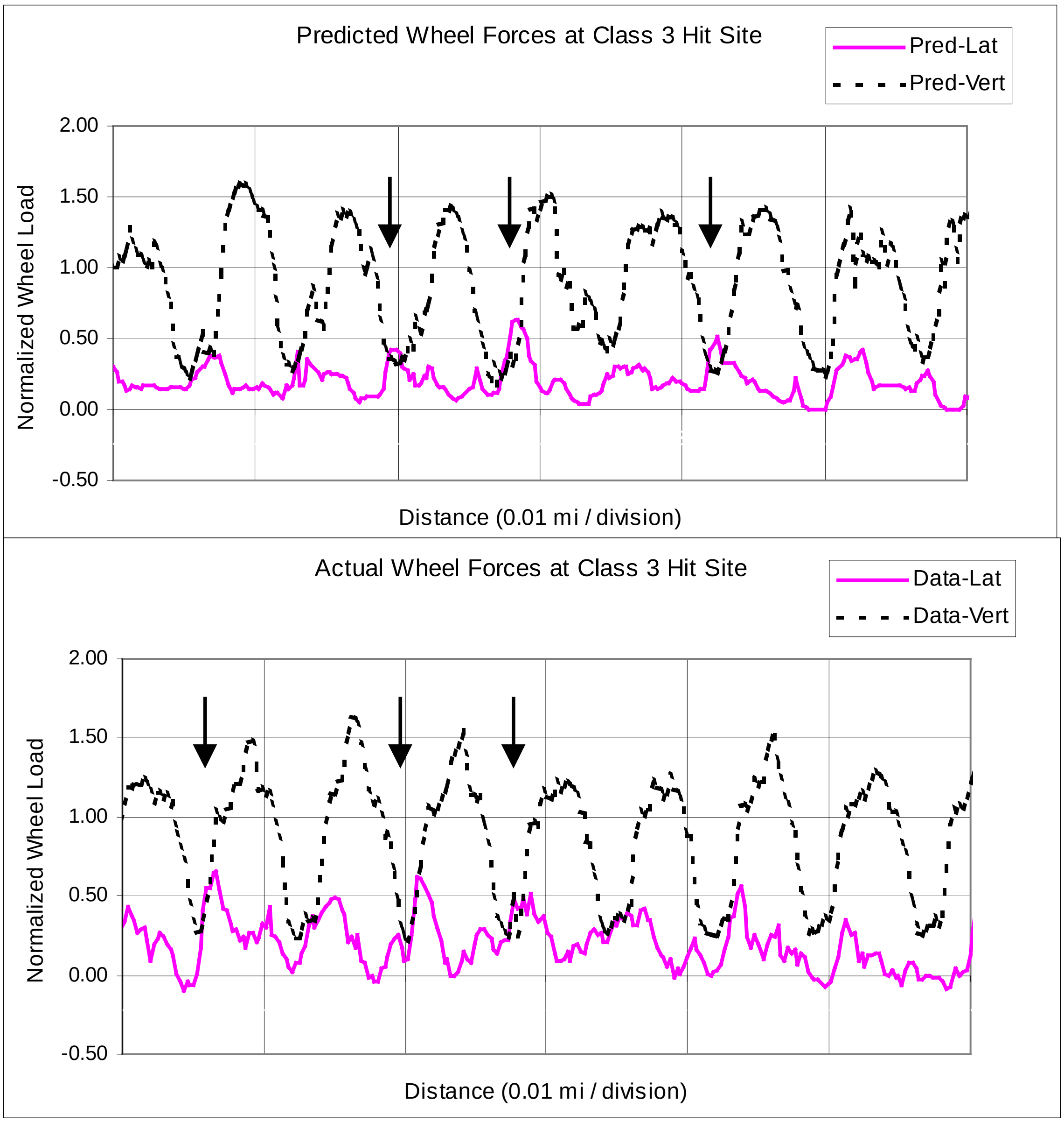

Figure 7 Comparison of measured and predicted forces

The program evaluates an entire subdivision by successively advancing the “window” along the track in discrete distance intervals and calculating the response. Once calculated, the predicted response for each car type and speed is evaluated against threshold levels for each car/speed combination and reported where exceeded.

3.3 Threshold Criteria

The specific threshold that was set in the analyses of the data presented in this report is a surrogate of “undesirable” vehicle response; however, “undesirable” response levels do not necessarily predict a state of imminent derailment.

The L/V force ratio used to predict derailments for wheel climb was developed by Nadal. Nadal’s formula considers the force ratio required at the flange-rail interface to sustain wheel climb after tread lift-off. The formula defines the threshold of acceptable ratio of L/V force at the flange interface.

$$L/V \leq (\tan\alpha - \upsilon) / (1 + \upsilon \tan\alpha) \qquad (1)$$

where:
L = lateral wheel flange force
V = vertical wheel flange force
α = the flange contact angle
υ = the flange-rail friction coefficient

The formula’s prediction of critical L/V ratios is sensitive to gauge face friction, while the lateral force levels that develop in a curve are sensitive to the tread friction at the low rail. A simplified illustration of the dominant forces developed at the lead axle of a conventional three-piece railway truck during curve negotiation is presented in Figure 8, which excludes the axle and shows the wheel’s two interface points with the rails. In shallower curves, the contact patch between low rail head and wheel tread exhibits both sliding and rolling contact, and develops lateral creep forces that are based on a proportion of the coefficient of friction that exists in the contact patch. In tighter (higher degree) curves the wheel-tread at the low rail is in full sliding laterally across the railhead and develops a creep force based on the full coefficient of friction in the contact patch. The curving force that overcomes the lateral creep force developed at the wheel tread on the low rail is established at the wheel-flange / gauge-face interface at the high rail. Thus, the low rail’s head friction has a significant influence on the lateral force that is produced at the wheel flange interface at the high rail.

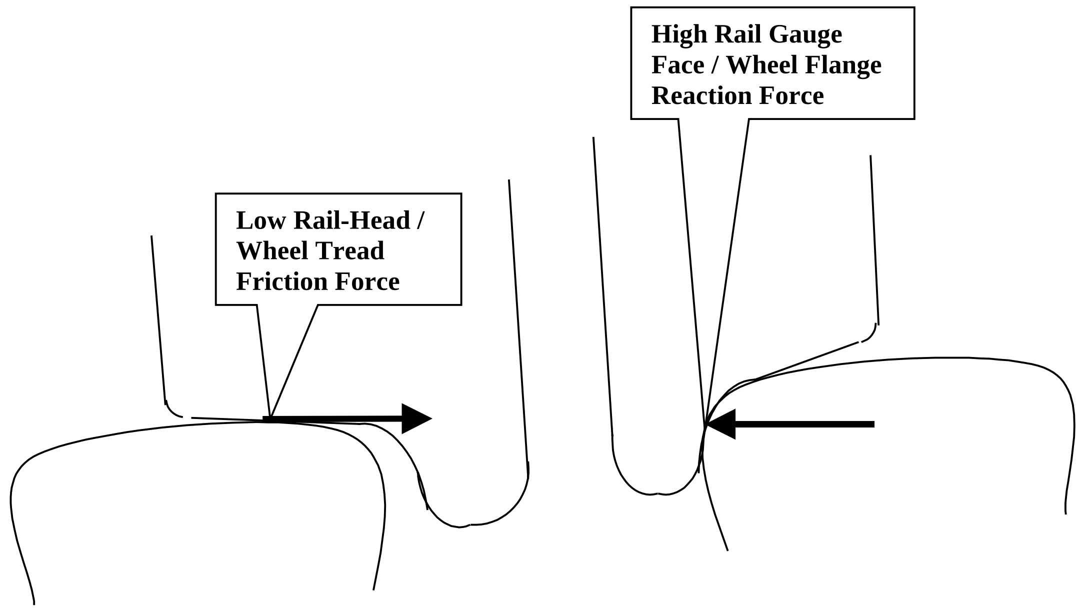

Figure 8 Simplified illustration of friction-related curving forces

Figure 9 shows that for a new-wheel-condition flange angle of 75 degrees, the threshold value of 1.0 corresponds to an extremely dry friction condition of 0.6. A lubricated gauge face with friction less than 0.25 would have a threshold of 1.75.

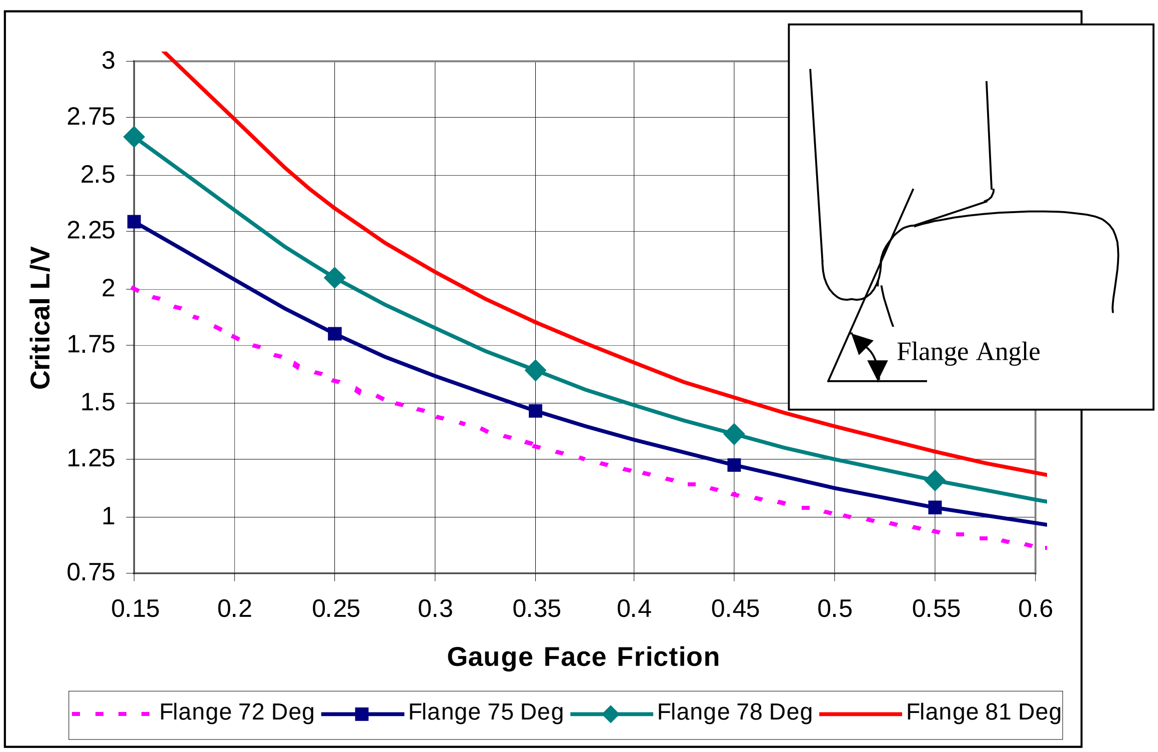

Figure 9 Nadal's formula of critical L/V

Chapter eleven of the Association of American Railroads Manual of Standards and Recommended Practices [AAR, 1993] presents a criterion for dynamic response to track irregularities by which new rail cars are certified. The evaluation of new car designs involves an assessment of car response to a perturbed test track.[2] Car response is measured with fully instrumented wheelsets. The instrumented wheelsets provide an indication of both the lateral and vertical forces at the wheel and thus allow for the determination of a lateral-to-vertical (L/V) force ratio.

The "roll" test is conducted under both empty and fully loaded conditions, while the "bounce" test is conducted at a fully loaded state. For a car to be certified, it must not exceed the following limits for a period greater than 50 ms:

- a minimum vertical load of 10 percent of the static load (bounce/pitch or roll)
- a maximum L/V of 1.0 (roll/twist)

The AAR's L/V threshold value of 1.0 is associated with acceptance testing of new cars. The L/V threshold value adopted in the U.K. for track design/repair is 1.2 [Railtrack, 1993]. We have used these two thresholds in the predictor model, such that a L/V threshold of 1.0 triggers a base-response category, and exceeding a threshold of 1.2 triggers a priority-response category.

The measured data identified only three occurrences at two sites of tangent track L/Vs exceeding 1.0. Two of the locations involved track segments where the alignment data channel was dropping out and thus provided no basis to predict the lateral forces. Also, there appears to be very little opportunity to maintain a lateral force for a sufficient duration to achieve wheel climb in tangent track. The force histories measured at the tangent track hit sites support the hypothesis that the axle will self-correct in low curvature (< 2 degrees) situations.

The forces are illustrated in Figure 10. One can see that at both hit locations (i.e., time units 121 and 340) the direction of the lateral force is increasing at the same time the vertical force is decreasing. However, as soon as the force ratio reaches 1.0, the lateral force drops off such that the force ratio is limited to a magnitude of 1.0 throughout the cycle. In tangent track there is no steady-state curve force to maintain the lateral force. The lateral force acts on the axle to mitigate the magnitude and as soon as any wheel

2 The test track perturbations involve track characteristic of jointed rail settlement (a rectified sine wave with a 39 ft. period). The "roll" test track presents a 3/4 in. variation with left and right side rail joints offset by 18.5 ft., while the "bounce" test presents a 3/4 in. variation with left and right side rail joints coinciding at the same locations.

climb is initiated, the increased rolling radius at the flanging wheel will offer a self-correcting mechanism. Thus, the model does not evaluate tangent track as an L/V risk. It does predict locations of 90 percent unloading in tangent track due to bounce lift-off as verified in phase 1.

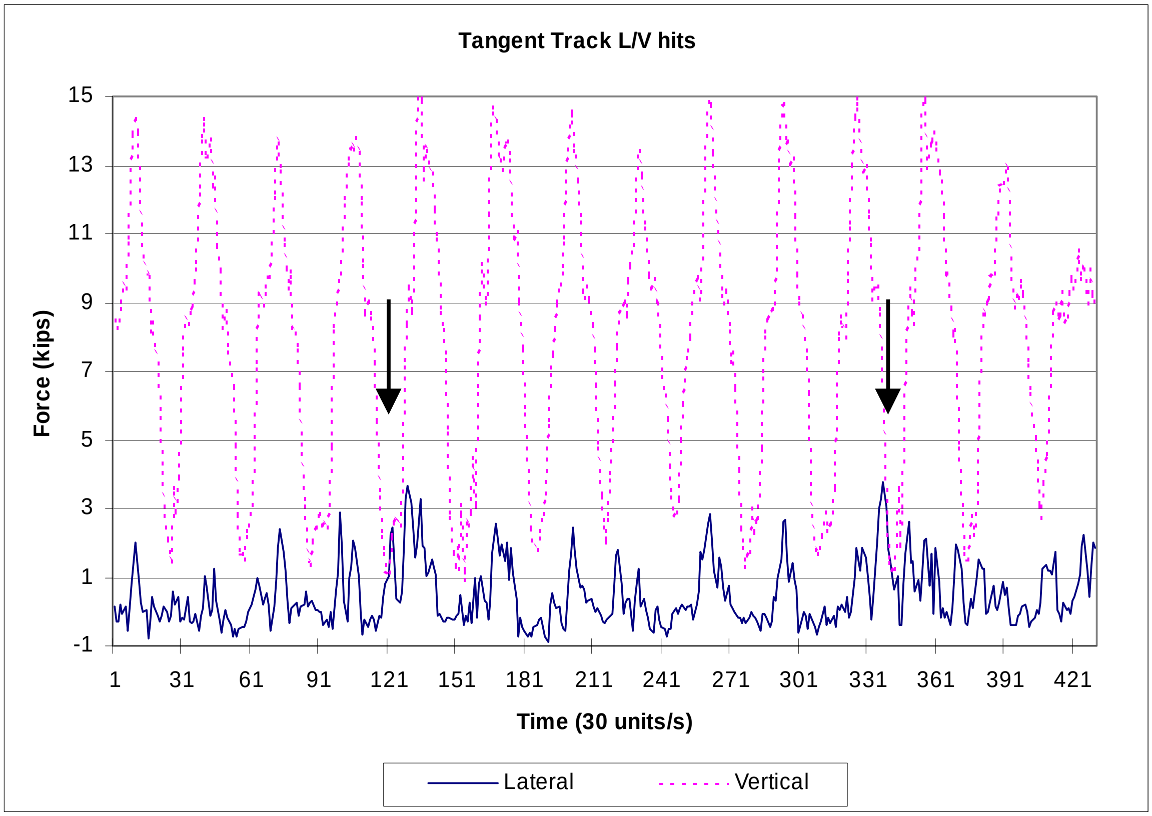

Figure 10 Lateral and vertical forces at tangent track hit site

4 ACCURACY PERFORMANCE

4.1 Test Car Characterization

The loaded car produced no L/V readings above 0.55. However, the car was loaded with a dense product, which resulted in a low centre of gravity. A higher centre of gravity and lower test speeds would be expected to result in more dynamic action. Assessment of derailments of loaded cars with geometry as a contributing factor is recommended for follow-on work. Even though the L/V ratio was consistently low for the loaded car, the loaded car demonstrated greater force variations than the empty car. As such, the loaded car's dynamic response is important in locating sites that generate high track force variations and stimulate higher rates of deterioration. Thus, even though it is less important from a derailment risk at these speeds, loaded car response might be considered as a performance measure for maintenance prevention viewpoint.

Since high L/V prediction was the focus of this phase of research, and the loaded car did not experience any high L/Vs, it is not included in the remainder of this section. The accuracy comparison was made with the empty car, using its particular characteristics. Thus, predictions were compared for the lead axle of the lead truck, and the right side suspension was made stiffer and the damping rate was set lower than for the left side.

4.2 Class 2 Track, Prairie Terrain Comparison

The subdivision that exhibited the highest hit rate was the same subdivision that generated a high frequency of vertical unloading in phase 1. However, while the phase 1 generated close to 2,000 occurrences of unloading greater than 80 percent, the L/V tests resulted in 17 hits involving 16 sites with L/V greater than 1.0 for the lead axle of the lead truck at the test car's speed.

The resulting predictions for a Class 2 prairie subdivision are compared with actual hit sites in Figure 11. The measured L/Vs that exceeded 1.0 are shown as squares in the plot while the predicted L/Vs that exceeded 1.0 are shown as vertical solid lines. As illustrated, 14 hit sites are predicted, while 2 are missed. One of the missed hits had intermittent dropouts of the left alignment measure that precluded the prediction of lateral forces. The figure also illustrates that there were 12 false positive predictions (predicted hits that did not occur in the measured data). Of the 12 false positives there were three locations where quite high L/Vs are predicted, while the measured L/V was less than 1.0. The characteristics of representative false positive sites are discussed in detail in chapter 4.

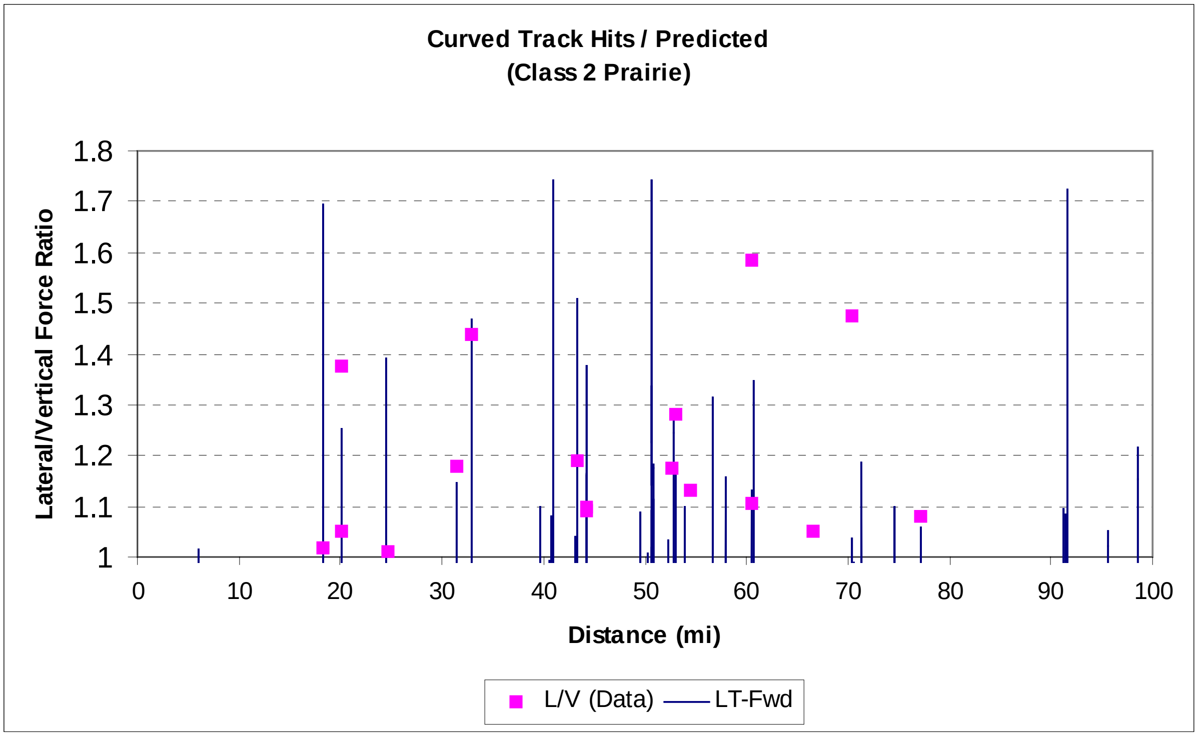

Figure 11 Predicted/measured hit comparison for class 2 prairie subdivision

One factor contributing to the frequency of unloading at the high rail in this Class 2 subdivision is the overcompensation of the curves. The line had once been used for higher speed passenger service and all curves are overcompensated for the present train speeds. While this situation exacerbates the frequency of vertical unloading, it also provides a mitigating factor by lessening the lateral forces developed in the curves.

4.3 Class 3 Track, Mountain Terrain Comparison

The test route covered three different mountain subdivisions, but all of the hits occurred in only one of them. The model predictions are compared with actual hit sites in Figure 12. The measured L/Vs that exceeded 1.0 are shown as squares in the plot, while the predicted L/Vs that exceeded 1.0 are shown as vertical solid lines. Five of the six hit sites are predicted, one is missed and there are two false positives. The mountain region L/V site that was missed with the predictor model involved lateral forces that exceeded those measured in other curves with similar measured characteristics, while the false positives had lower than normal lateral forces. The contributing factors involved at false positive sites are discussed in detail in section 4.6.

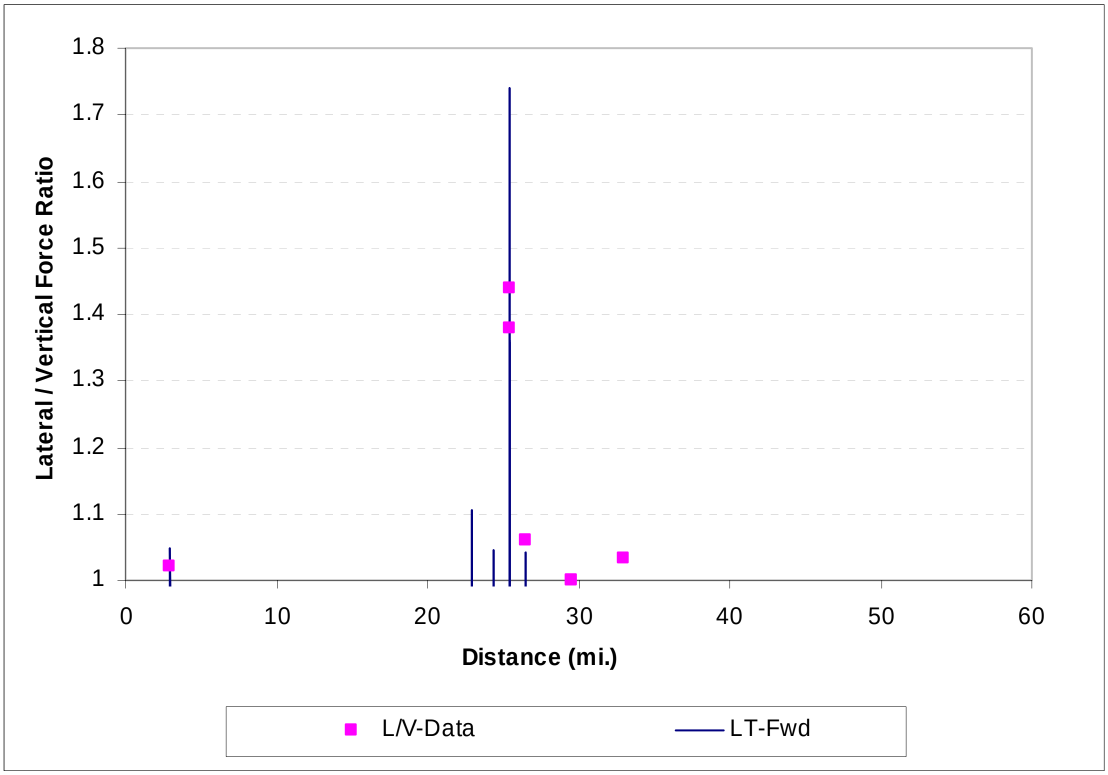

Figure 12 Predicted/measured hit comparison for class 3 mountain subdivision

While the prairie region hit sites were associated with harmonic roll, the mountain region hit sites involved twist and higher lateral forces. The only left side hit measured during the test occurred in a 10-degree curve in the mountain region. Figure 13 shows the measured wheel forces at the high rail and geometry at this site. The top plot is the forces, the middle plot contains the curvature and superelevation, and the lower plot contains the left and right rail alignment.

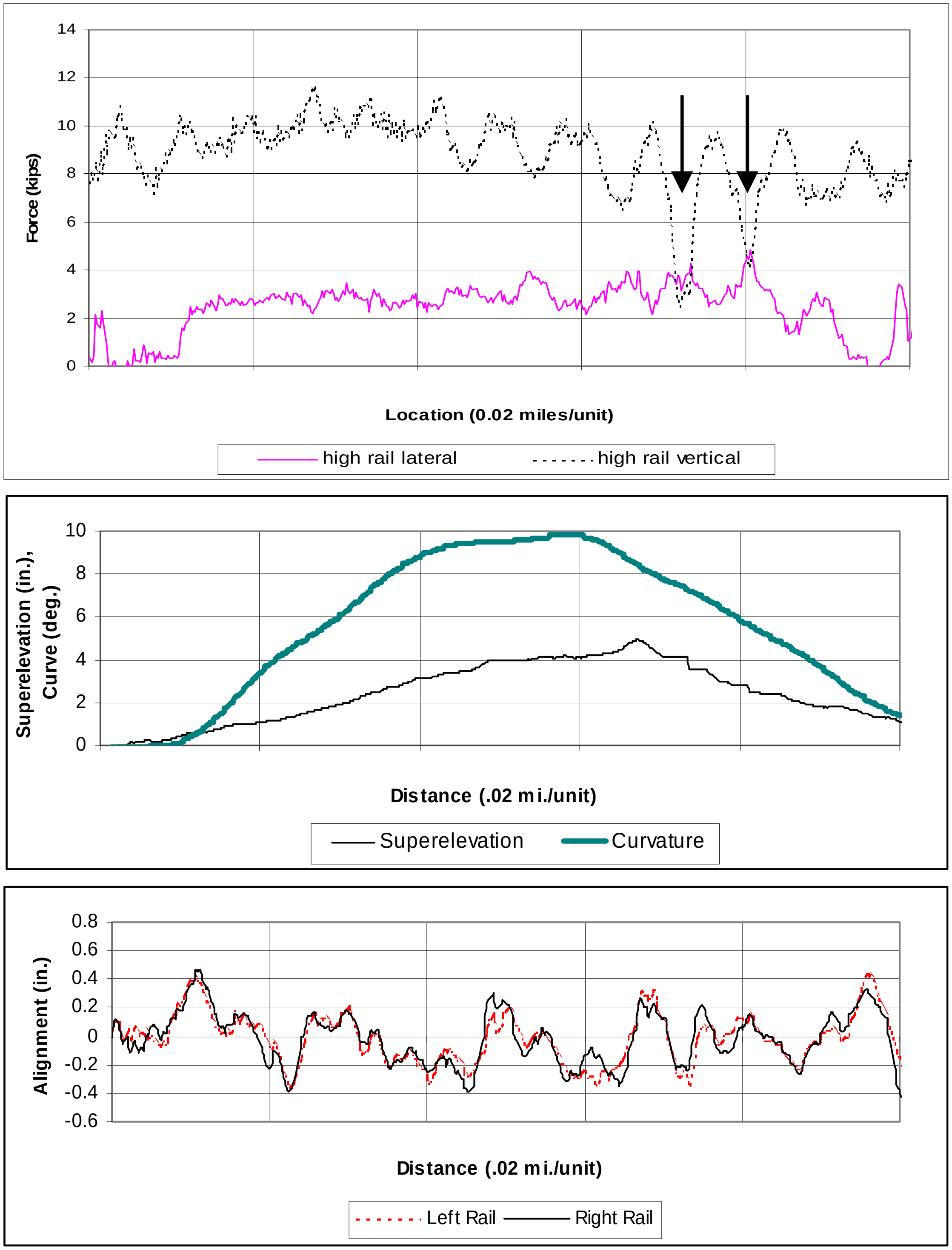

Figure 13 Geometry and wheel forces at mountain hit site

4.4 Summary Table

Table 4 summarizes the accuracy performance of the predictor model for all test subdivisions.

Table 4 Summary of prediction accuracy for complete test route

Region	Measured Data			Model Predictions		
	Track Class	**Data-miles**	**L/V > 1**	**Predicted**	**Missed**	**False Positives**
Pr.	Class 2	100	15*	14	1	12
Pr.	Class 2	60	3	2	1	1
Pr.	Class 3	50	0	0	0	0
Pr. + Mtn.	Class 4	136	0	0	0	0
Mtn.	Class 4	60	6	5	1	2
Mtn.	Class 4	116	0	0	0	1
Total		522	24	21	3	16

Legend:
Pr. Prairie (maximum curvature 3 degrees).
Mtn. Mountain (maximum curvature 11 degrees).

4.5 Examples of False Positive Predictions

In general, the false positive predictions can be explained by variations in the non-measured parameters and/or involve track segments that are very close to generating a high L/V. The remainder of this section provides examples of false predictions for the class 2 low curvature subdivision and the class 4 high curvature subdivision.

4.5.1 Class 2, Low Curvature

Figure 14 illustrates the measured vertical forces and high-rail lateral force at one of the false positive sites registered for class 2 track with a 3-degree curve. While no L/Vs above 1.0 were registered for this site, the lateral and vertical force variations exhibit a significant overlap in magnitude that is always slightly out of phase. The predicted locations of L/V>1.0 are designated with the vertical arrows, while the length of the window reported by the model is designated by the horizontal arrows. While this site is technically a false positive prediction error, we believe that the forces are close enough to overlapping that a slightly different test car might have produced a hit at this location. In any event, the forces are such that we would not categorize corrective maintenance for this site as a misallocation of resources.

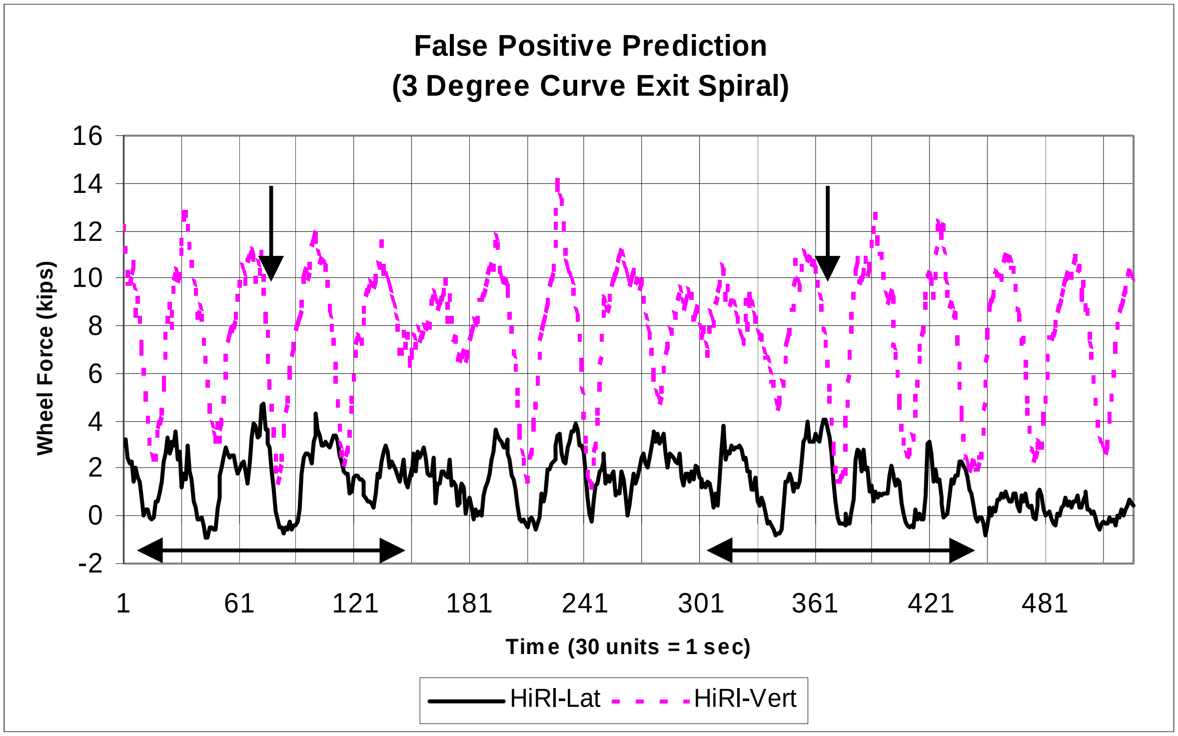

Figure 14 Measured forces at false positive low curvature site

4.5.2 Class 4, High Curvature

The actual data measured at the site of one of the high false positive predictions in the mountain region is illustrated in Figure 15. A hit was predicted in the exit spiral at the location indicated by the vertical arrow. The 8-degree curve exhibited measured lateral forces that were less than half those measured in previous and later curves of 6 degrees. One possible explanation for the unexpectedly low lateral forces is that lubricant had contaminated the top of the low rail in this curve. The curve would be expected to produce much higher forces under normal circumstances.

Another example of a mountain region false positive is illustrated in Figure 16. The model predicted an L/V greater than 1.0 in the fully developed portion of the left-hand curve (negative on the plot) at MP 21.204. A dynamic lateral force increment can be seen to occur at this location; however, the overall average force developed at the low rail is low relative to the subsequent right-hand (positive values) curve. It is also low relative to other left-hand (negative) curves of the same magnitude.

Our lateral force is based on a level of friction at the low railhead that is larger than the forces exhibited in both the above examples. Section 4.6 discusses the influence of non-measured factors on L/V force ratios.

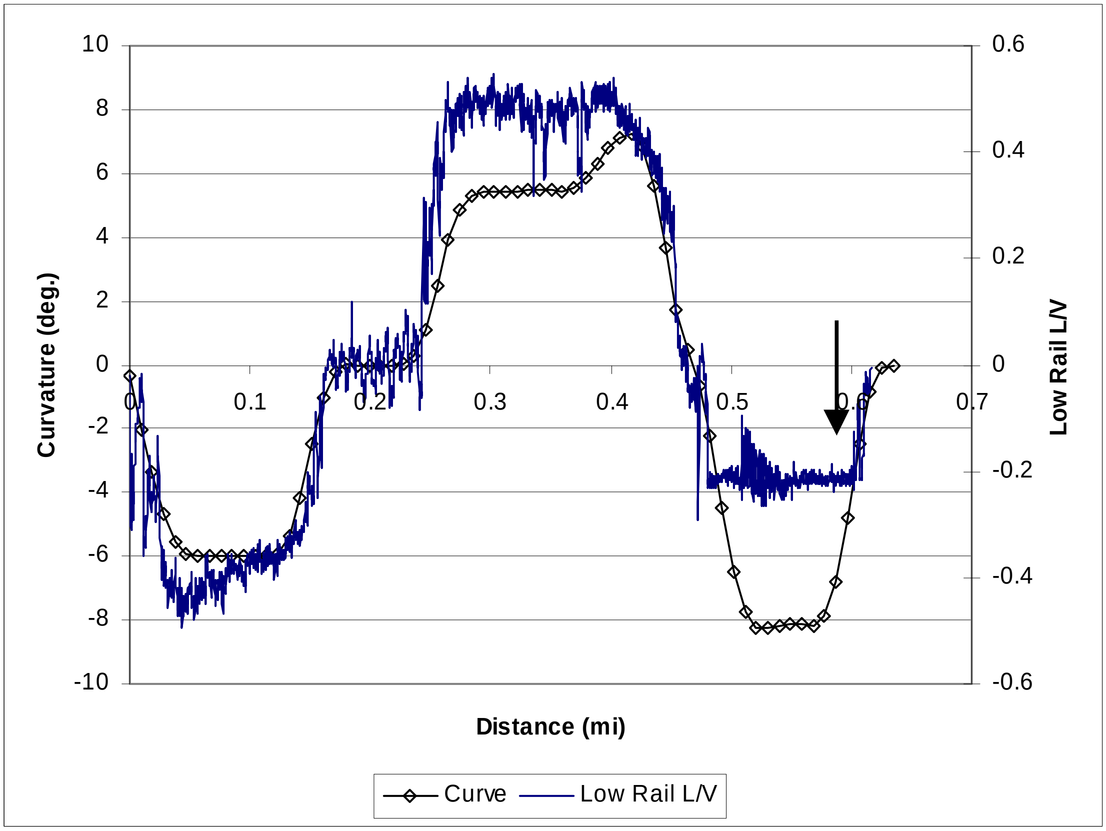

Figure 15 Measured low-rail L/V at false positive high curvature site

Note: Negative values of curvature indicate left hand curves, positive values are right hand curves.

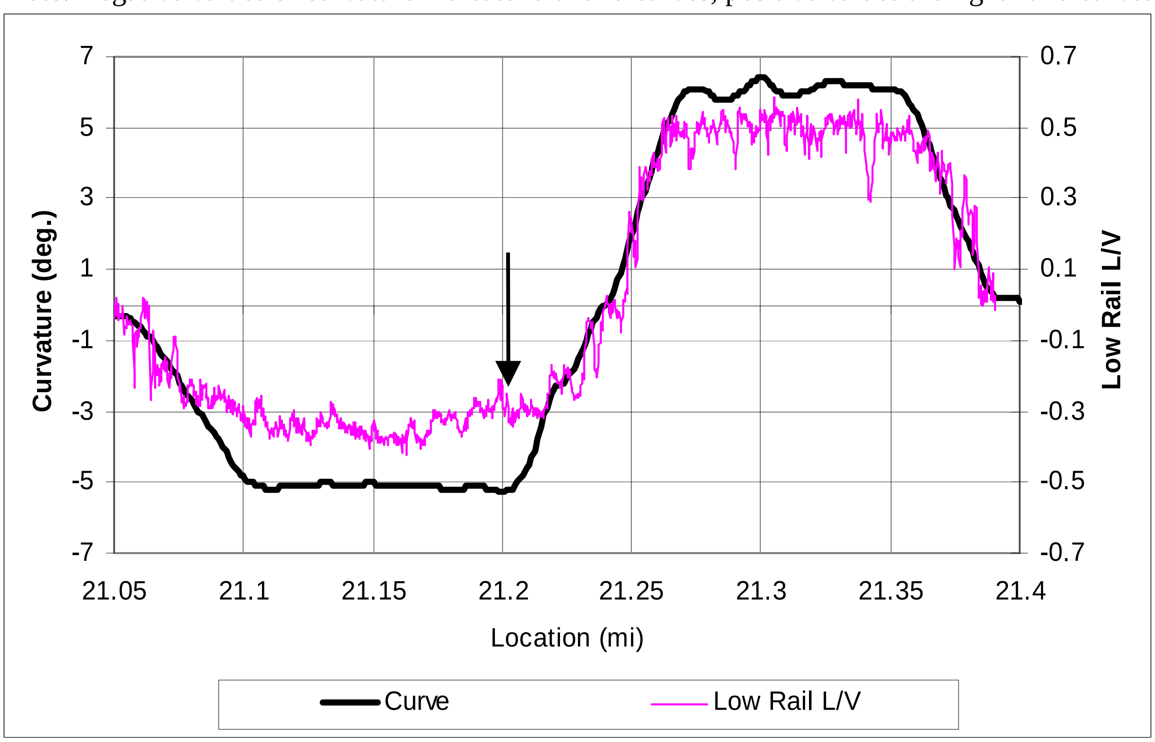

Figure 16 Measured L/V at low rail of second false positive mountain region

4.6 Influence of Non-measured Track Factors

In the process of validating the predictor model, a number of non-geometry variables were identified that have a significant influence on the predictions of the model. These variables (which include both vehicle and track parameters) are assigned single values in the model, but the measured data illustrate that they exhibit a variation in reality that influences the accuracy of the prediction.

4.6.1 Track-Side Factors

Friction between wheel and rail is a key factor in predicting high-risk geometry conditions. The importance of gauge face friction in determining the allowable magnitude of L/V ratio that will produce wheel climb was illustrated in Figure 9. In addition, the friction at the railhead / wheel-tread interface on the low rail is an important factor in the development of lateral forces in curve negotiation, as was illustrated in Figure 8. This friction level can be expected to vary with environmental conditions and also with location.

The steering committee for this project indicated that in passing through reverse curves trains have a tendency to carry lubricant from the high rail's gauge face in the first curve to the low rail tread of the subsequent curve. Thus, one can expect friction levels to be lower in reverse curves and possibly vary with the distance from the previous curve. This condition is evident in the curving forces exhibited in some of the reverse curves that were traversed in the test.

This phenomenon of railhead contamination of the low rail in reverse curves is a possible explanation for the two false predictions in the mountain territories and illustrated in Figure 15 and Figure 16. The influence of low rail friction on the lateral force at the high rail gauge face was discussed in section 3.3.

Conversely, the average curve force at the hit location that was not predicted demonstrated lateral forces much higher than measured at other locations of similar curvature. The L/V ratio at the low rail at the missed hit site was three times larger than that measured at the false prediction of Figure 15 and about 20 percent higher than measured at any other curve encountered in the test route.

It would be feasible to measure the friction levels of rails with the track geometry car. However, there would be little benefit since the friction level will vary from season to season and will be influenced by the condition of lubricators and the transport process of trains that pass over them. The fact that these conditions vary simply implies that the model must use a reasonable assumption of a possible friction level. For the accuracy comparison, the values were chosen to give a reasonable fit to the data. There are obvious tradeoffs involved in selecting the values of non-measured parameters assumed in the model. An accuracy focus leads to a balance between false positives and missed sites. A conservative adoption of worst-case assumptions would identify all hit sites but significantly elevate the number of false positives. Since the L/V threshold is in itself a conservative one, we believe that the number of missed hit sites inherent to the present model assumptions is a reasonable trade-off. Nonetheless, the assumptions that should be used in a final implementation need to be considered by the user.

4.6.2 Vehicle Factors

The previous phase of research focused on vertical unloading at the suspension and used conservative estimates of wheel loads related to suspension loads. The result was that very high frequencies of unloading were predicted for class 2 track. One of the objectives of this phase of research was to gain insight to the relationship between wheel loads and suspension unloading and to see whether the number of sites that are identified as undesirable becomes more manageable with the added insight to lateral and vertical wheel forces. The present phase measurements of wheel force indicate that when the car body unloads, wheel forces do not vary significantly from the average weight of the truck. The vertical wheel load relationship assumed in the previous phase was too conservative and has been updated in the model to reflect the wheel load data.

There are other vehicle-side factors, which are known to vary and must be assumed in the predictor model. The stiffness and friction damping level of the car's suspension are key assumptions. Another important factor that is measured for the test run but that must be assumed for the normal implementation is vehicle speed. Its importance was demonstrated in phase 1 and is illustrated later here in section 4.6. In addition, the in-train braking forces and car-position-in-train can have a significant influence on the magnitude of lateral forces.

Phase 1 identified a phenomenon of higher damping of vertical dynamic response in curves, and hypothesized that the lozenging motion (or parallelogramming) of the truck produces a tighter fit and a higher friction force between the wedges and the side frame's wear plates. The measurements made in this phase confirm that this does happen. The energy dissipated in the friction forces of the empty car's suspension is significantly higher when negotiating curves than it is on tangent track. This can be seen by comparing the area of the hysteresis loops for the empty hopper car as illustrated in the force-displacement plots of the empty cars suspension for a 10 degree curve (Figure 17) and tangent track (Figure 18).

Figure 17 also illustrates a significant difference in the stiffness of the left and right suspensions. The slope of the force displacement curves is a measure of spring stiffness. The stiffer suspension will demonstrate larger force change when encountering the same displacement. As a consequence, the stiffer and less damped right side suspension produced all but one of the L/V hits experienced by the empty hopper car.

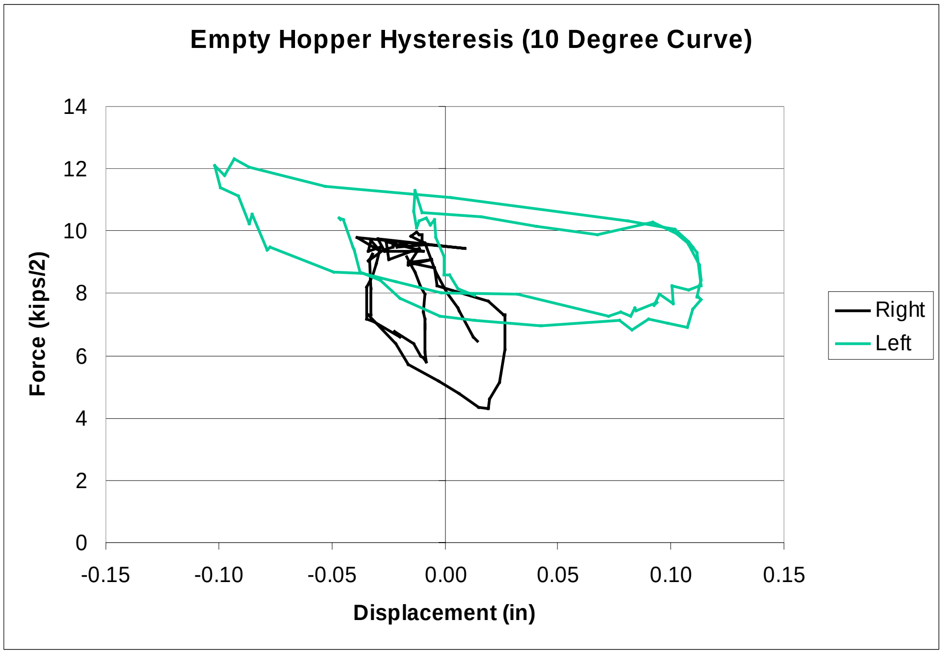

Figure 17 Hysteresis of empty car in 10 degree curve

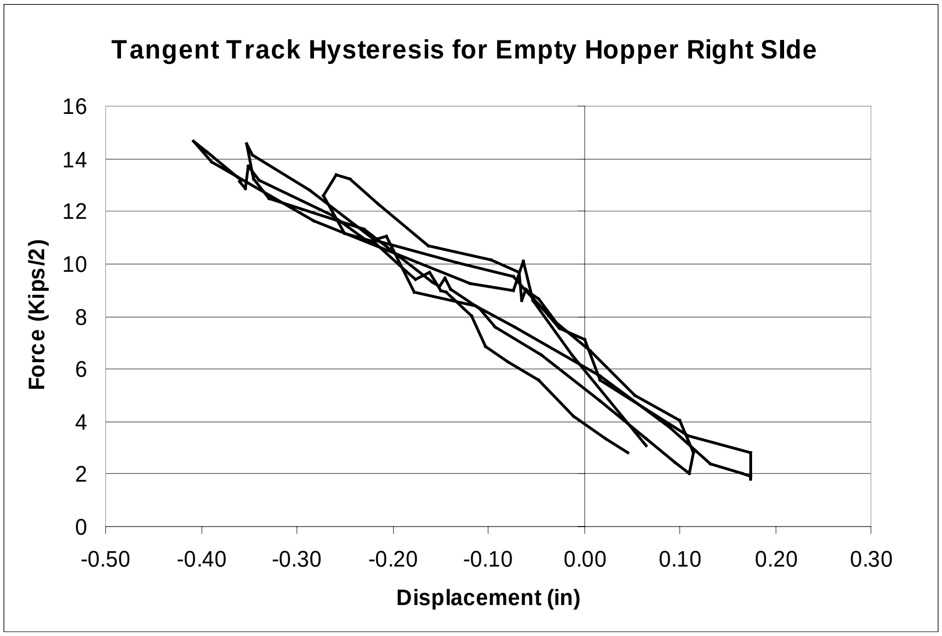

Figure 18 Hysteresis of empty car in tangent track

4.7 Final Model Output Comparison

The accuracy comparisons made in chapter 4 were based on the actual test car suspension characteristics and running the predictor model at the test car's speed. The predictor model, when used in normal operation, assumes the right side suspension for all suspension points and considers the car's critical speed as well as the posted speed limit for each track segment. It also assesses forces at the trailing truck and for the car running in the opposite direction. Thus, the number of predicted sites with L/V greater than 1.0 for the final model exceed those predicted for the test car.

Two of the mountain subdivisions did not experience any hits and none where predicted for the test conditions. However, if the model is run in its final form with the more critical speed of 25 mph as well as the speed limit and considering all axles running in both directions of travel, hits are predicted. This is seen in Figure 19, which presents model predictions for one of the mountain region subdivisions with 136 mi. of mixed Class 3 and Class 4 track.

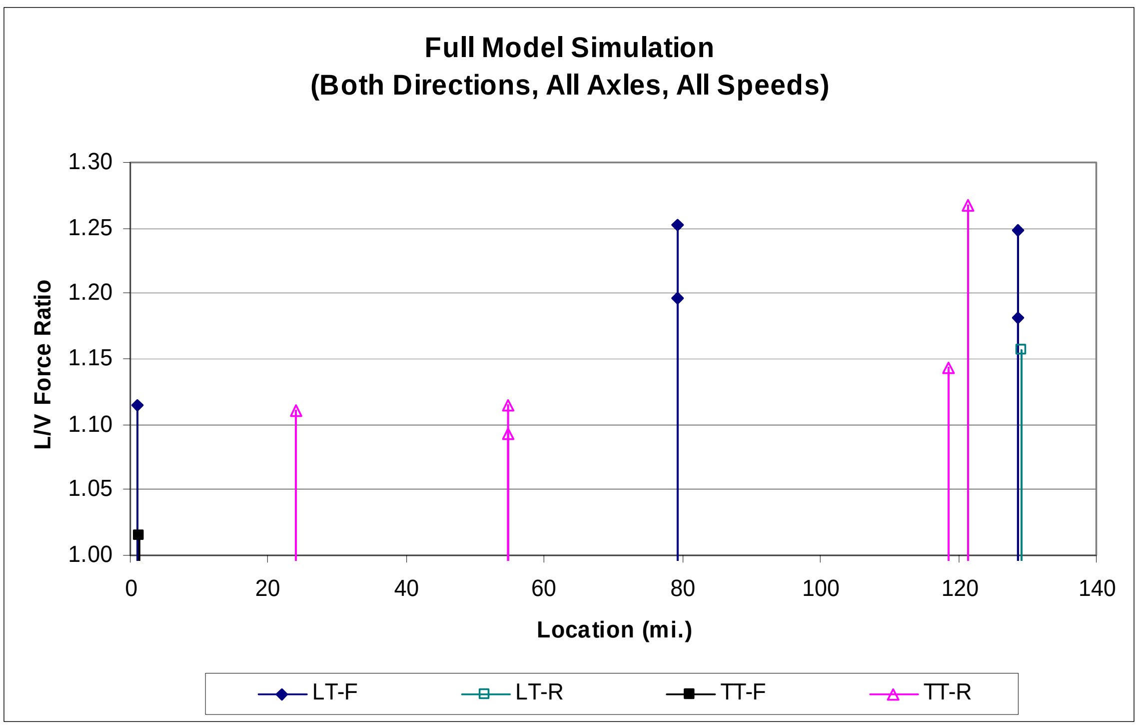

Figure 19 Predictor output for all axles, all speeds and both directions

This subdivision had no L/Vs greater than 1.0 measured or predicted for the lead truck at the test train's speed. However, the model predicts 12 occurrences of L/V greater than 1.0 for non-test conditions. The "LT-F" hits are for the **L**ead **T**ruck in the **F**orward direction, which was the measured axle; however, the hits are predicted at other speeds than the test speed. All other predicted hits involve axle positions and/or travel directions that were not tested (i.e., LT-R (**L**ead **T**ruck in the **R**everse direction), TT-F (**T**railing **T**ruck in the **F**orward direction), TT-R (**T**railing **T**ruck in the **R**everse direction)).

5 RELATIONSHIP TO DERAILMENTS

Various derailment analysis tasks were performed to asses specific implementation features and the operational performance of the track performance predictor model in relation to conditions that were known to be in existence at the time of actual derailments. Specifically, these included examination of the track geometry features and other circumstances at identified derailment sites on main track in Canada, a review of several detailed derailment investigation reports and the development of time domain simulations to more closely examine specific rail vehicle response to defined track geometry excitation.

The major resources for these analyses were: a list of main track geometry-related incidents that occurred on CPR territory in Canada between 1998 and 2002 as provided by CPR, a list of Canadian main track derailments between 1998 and March 2003 as provided by Transport Canada, and several comprehensive reports on investigations conducted into derailments that occurred in Canadian mountain terrain. The following sections elaborate on the work conducted in each of these task areas.

5.1 Main Track Derailments

Historical derailment data obtained from CPR and Transport Canada were used to identify candidate locations for subsequent detailed review. The information provided by CPR identified all incidents that occurred on its main track subdivisions having track geometry causes assigned, excluding those attributed to wide gauge, from 1998 to 2002. The information provided by Transport Canada identified all incidents that occurred on Canadian main track between 1998 and March 1993 and were assigned either track geometry or undetermined causes or contributing factors.

The main track incident information typically identified the date, time and location of an incident and provided some general details of the circumstances such as direction and speed of travel, the rail vehicles involved, and often a brief synopsis of the event. Details of the track geometry at the incident location were not included with this information, although the incident categorization often identified the general nature of track geometry features considered by those investigating the incident to have had a contributing influence. The derailing rail vehicles were identified by car number, type and lading status (either loaded or empty), with no further details regarding the physical characteristics or wear condition of car components.

Since no detailed track geometry information accompanied the historical main track incident information, and since this information was not obtainable from other sources, the scope of the derailment analysis was necessarily limited to a time period for which TranSys Research Ltd. had previously collected track geometry data during field testing in an earlier phase of work. These track geometry data encompassed many CN main track subdivisions tested between November 2000 and August 2001 by the CN TEST track geometry car and many CPR main track subdivisions tested by a CPR TEC consist between January 2001 and October 2001. Both track geometry consists had special equipment and procedures implemented during theses periods to facilitate collection of these data.

The scope of the main track derailment analysis was limited to the time period between November 2000 and the end of 2002, during which a total of 23 geometry-related derailments were identified. However, upon closer examination, many of these could not be considered because they were caused primarily by frost heave conditions, ballast settlement or subgrade loss—all track-related incidents, but not associated with the conditions measured by the track geometry car. Of the remaining sites, relevant geometry data were available for only one incident, which occurred in mountain territory.

In the mountain territory derailment, the leading axle of an empty hopper car derailed in the fully developed portion of a 6-degree curve in August 2002. While there were no defects detected during the most recent pass of a track geometry car in the track leading up to the point of derailment, reported to be mile 79.1, two dips in the low rail surface track geometry were noted within approximately 100 ft. prior to the point of derailment. One was found to measure 1.1 in. in 20 ft. while the other was 0.6 in. in 15 ft. Also, of particular note was the significant amount of wedge wear on the derailed truck, which had an average wedge rise of 0.6 in. This amount of wedge wear, while well below the AAR wear limit of 0.75 in., would have resulted in a significant reduction in suspension damping, thus making the car particularly sensitive to dynamic stimulation. The investigating authorities concluded that this derailment was caused by excessive car body roll response induced by track geometry input to the car having a “somewhat worn” truck condition.

The most recent track geometry measurements recorded at 1 ft. intervals, which TranSys had available for this subdivision, were taken in March 2001. As more than a year had passed from the time those measurements were taken and the time of the derailment, a copy of the most recent track geometry for the subdivision was obtained directly from the railroad. The newer track geometry provided was recorded at 5 ft. intervals in April 2002.

Figure 20 illustrates the gauge, superelevation and curvature measured in the vicinity of the point of derailment. Curvature and gauge did not vary significantly for the three measurement dates and are only shown for one timeframe. Superelevation did vary and is shown for each of the three measurement times. The track superelevation throughout the 6 degree curve as measured in March 2001, April 2002 and again in May 2003 has noticeable differences, but evidence of a perturbation in the superelevation near the point of derailment appears to be consistent.

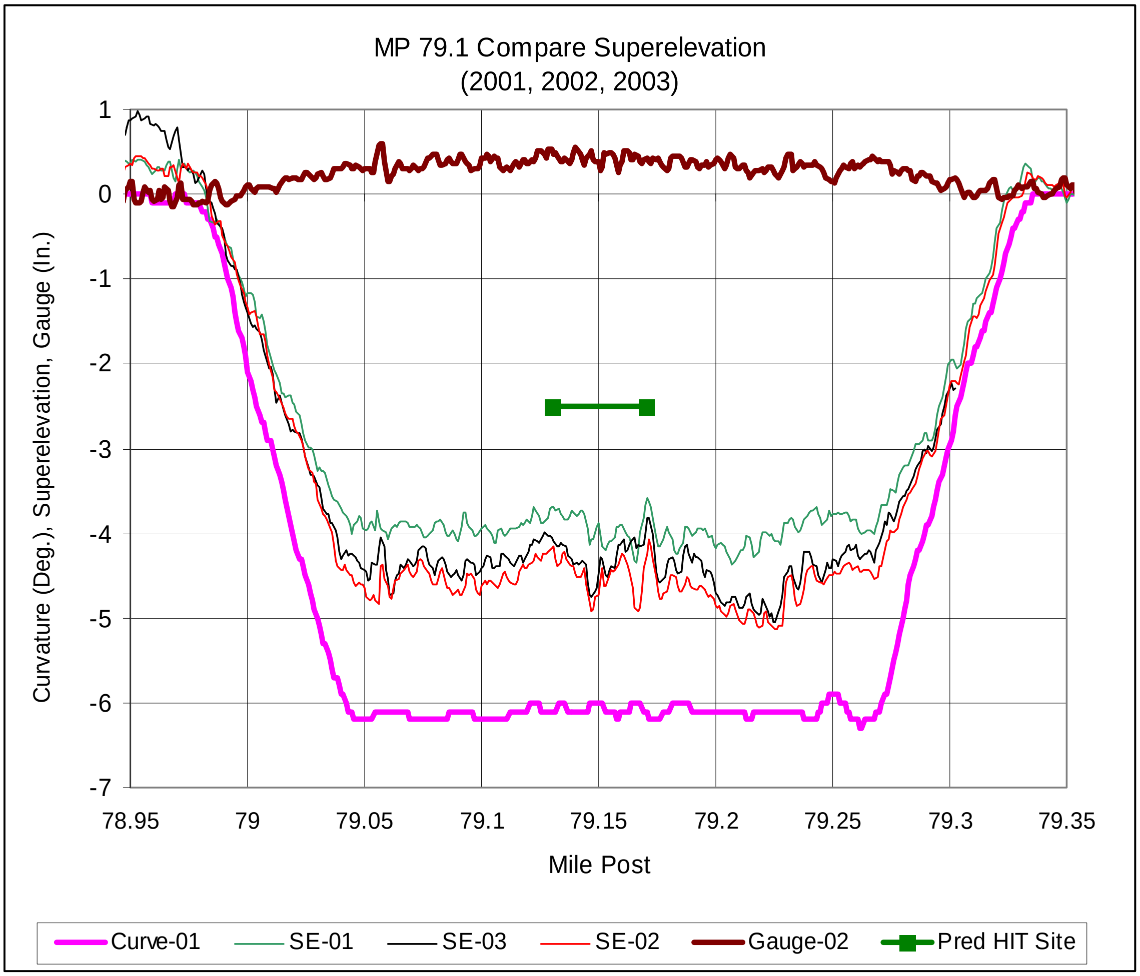

Figure 20 Geometry measurements at derailment site

The two track geometry files recorded for this subdivision in 2001 and 2003 were each processed through the track performance predictor model—the 2002 data were only available in 5-ft. intervals and could not be used by the simulation model. The predictor results for the 2001 geometry data are summarized in the upper plot of Figure 21. The predicted L/V levels were less than 1.0 for the data measured 18 months prior to the derailment, with a maximum value of 0.87 for a the lead truck travelling in the reverse direction at 40 mph. The same curve was assessed with the geometry measurements of 2003, about nine months after the derailment. The results are presented in the lower plot of Figure 21.

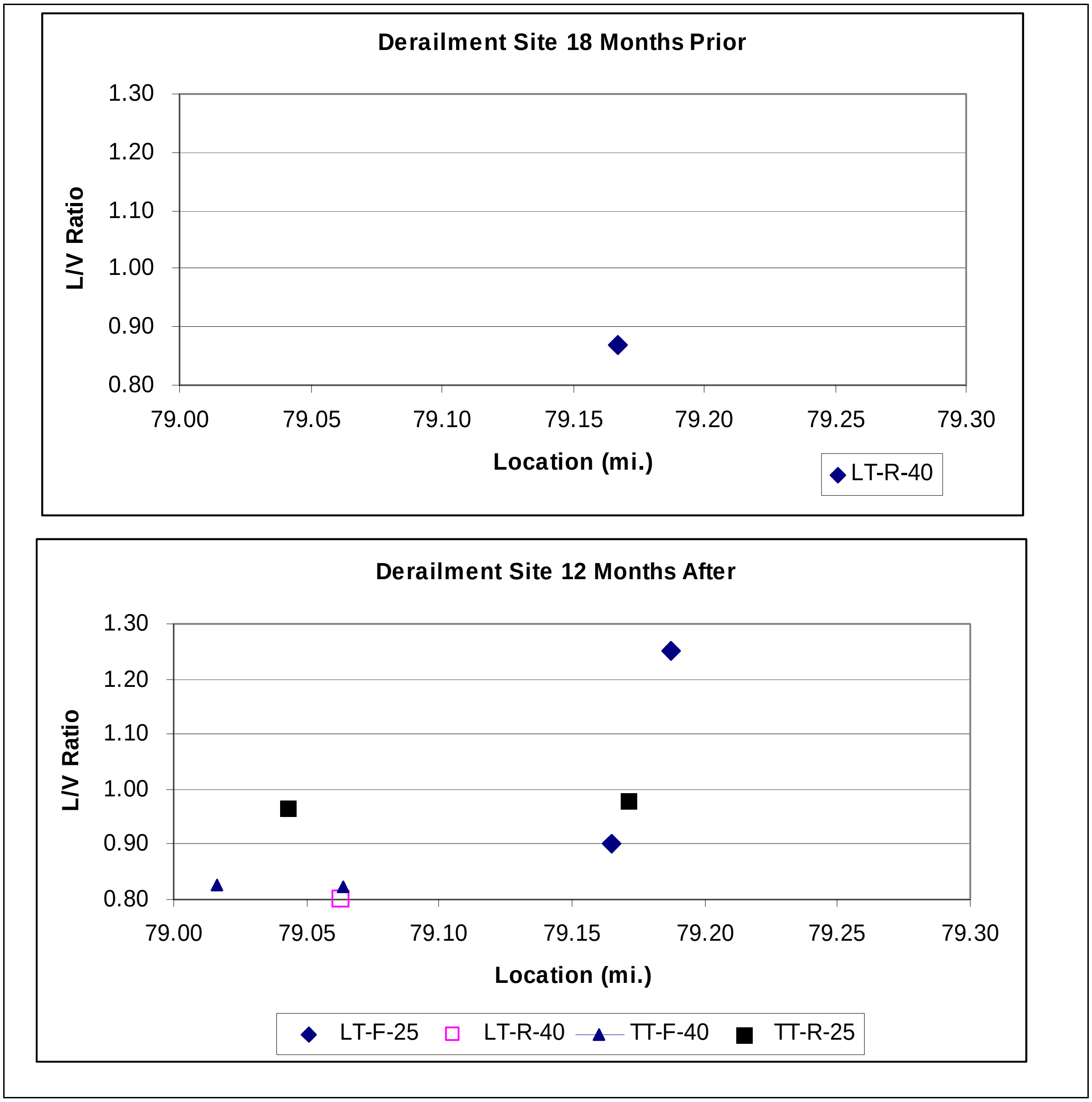

Figure 21 Predictor model results for derailment site

The 2003 model run indicates that the geometry at the site had deteriorated further. Seven L/V>1.0 conditions were predicted in 2003 compared with one in 2001. In addition, one of the predicted L/V values in 2003 exceeded the priority threshold level defined in the model as 1.2. Since the data for the 2002 run, which was closest to the time of the derailment, was saved in 5-ft. spacing, it is not possible to determine if the model would have found L/Vs greater than 1.0 for the location at that time. However, it is possible given the growth between the 2001 and 2003 measurements. Since the site does not exhibit any characteristics that exceed the existing geometry standards, no corrective maintenance steps would be initiated under regulatory standards.

Since the predictor identified hits in the vicinity of the point of this actual derailment, it is reasonable to infer that this particular combination of track geometry features is significant in terms of instigating poor car behaviour, yet is not identified for corrective action by existing track defect criteria. On the other hand, these conditions are clearly not guaranteed to cause a derailment. The fact that more derailments did not occur at this site reaffirms that derailments are probabilistic events that depend on the right set of circumstances of car condition, train handling and environmental factors rather than just a geometry condition. Nonetheless, geometry is the one set of parameters that can be most easily measured. Taking corrective maintenance at sites that are predicted to generate L/Vs greater than 1.0 might not be necessary in terms of imminent derailment prevention but will reduce the longer term risk of derailment at that site.

5.2 L/V Data Insights

The data collected in the current phase of research also provides some insight into the wheel climb mechanism and forces required for derailment. There were two sites that produced L/Vs in excess of 1.4. One was a Class 2 low curvature site, the other a Class 4 high curvature site. The two sites were quite different in characteristics but share the fact that both produced high L/Vs and neither led to derailment of the test car or of other cars in the subsequent 9 months following the test.

Our hypothesis for why derailments did not occur is different for each site. The low curvature site has no lubricators and demonstrated a high L/V without derailment. In this case, the hypothesis is that the lack of a high steady-state curving force allows the axle to react to the lateral force and move in the opposite direction before wheel climb is realized. This was illustrated in Figure 10, which showed how the lateral and vertical forces influenced each other after a L/V ratio of 1.0 was attained in tangent track.

The explanation for no derailments at the high curvature site is more readily seen in the theory used to assess wheel climb risk. As noted in Figure 9, the level of friction at the gauge face of the high rail directly influences the L/V ratio required for the wheel to climb the rail. Referring back to Figure 9, one can see that the derailment threshold predicted by Nadal’s formula for a lubricated gauge face condition (friction coefficient between 0.15 and 0.25) is in the range of 2 to 2.7 for a 75 degree flange angle.

Thus, while the L/V identifies a site of elevated risk of derailment, wheel climb remains a low probability event as long as the lubricators are working properly. A low friction level can accommodate large L/Vs without incident. Consequently, one of the first factors that maintenance personnel should address in response to a high L/V prediction is to ensure that high rail gauge face lubricators are functioning properly. If lubricators are working properly, the corrective action to the geometry condition that produces the high L/V can be scheduled at a convenient time. It also means that high curvature track segments without lubricators should respond to lower threshold sites with more concern.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A software program has been developed that can successfully identify track geometry conditions that stimulate L/V force ratios greater than 1.0. While the validation data are limited to the lead axle of the lead truck, the model can predict L/V ratios for lead axles of both trucks for both directions of travel, for multiple speeds and for multiple car types in real time. The model can be used on board a geometry car in a real-time interface with the generated geometry data files or as a post processor.

The measured data and software predictor identify L/V sites that are not identified by the present regulatory defect criteria.

The data indicate that a rail car's vertical suspension damping is increased in curves. This phenomenon has been explicitly incorporated into the model. Other non-geometry parameters influence the lateral force magnitude and the acceptable level of L/V that can be encountered without derailing. The non-measured parameters that are factored into the model but that take assumed values include:

- gauge face friction at the high rail
- rail-head friction at the low rail
- railcar suspension stiffness (deviation from nominal specifications)
- railcar suspension damping
- railcar centre-bowl friction
- railcar coupler forces
- vehicle speeds assessed

While the above factors take fixed values in the model, they will in reality vary from day to day and from train to train. It is possible that some assumed track parameters could be modified in the model by location. For example, gradient segments could assume coupler squeeze forces in the downhill direction and tension forces in the uphill direction; or curves with lubricators could assume lower gauge face friction. The parameters involved are relatively fixed and could be provided as a separate input file, but the data would have to be provided in some way. Without the information, which is the present situation onboard the geometry car, the best way to deal with these parameters is to make reasonable yet conservative assumptions in selecting values within the predictor model.

6.2 Recommendations

The findings indicate that track geometry conditions that are missed by the present regulatory definitions can be identified. However, the data also revealed situations of L/V levels beyond threshold in curves that did not lead to derailment. The relationship to actual derailment occurrences needs to be explored in more detail in order to select action thresholds. Similarly, the values selected for those non-measured parameters that influence the predicted forces need to be explored in more detail.

The model predicts locations of high L/V that result from combinations of geometry input. Unlike the existing single-measure thresholds, it does not have an automatic corrective action associated with it. It would be desirable to develop a field manual to assist in locating the contributing factors at the site and guiding the selection of action from a range of possible corrective measures.

The field tests took a route that included high curvature mountain terrain and low curvature prairie terrain. However, it had a relatively confined speed range and one car type. It would be desirable to extend the validation data to cover another car type and a wider speed range. It would also be desirable to traverse some segments in both directions to validate the predictor's performance for those axles that were not part of the present data set.

The next steps can be summarized under two categories, those involving model validation and those involving adoption of performance standards using any validated predictive model:

Recommended steps for further model development/validation:

- Extend the validation data range of L/V data to additional car type(s).
- Extend the speed range of the L/V validation data.
- Conduct some L/V measurements with the test car(s) run in both directions over the same track segment and at a range of speeds.
- Gather geometry and car data from past derailment sites and assess the ability of the model to identify the site assuming the empty hopper car, and assuming the actual car type involved in the derailments.
- Explore the sensitivity of prediction accuracy to car characteristics for the car types involved in the derailments identified above.
- Develop a field manual to help maintenance personnel locate the contributing factors at an identified hit location and prescribe a range of possible corrective actions.

Recommended steps for advancing adoption of model-based performance standards:

- Refine the estimated range of non-measured parameters that can be expected to occur at various locations, and assess the sensitivity of model predictions to different assumed values of each parameter.
- Assess the correlation of predicted hit sites with existing track standards, particularly at historic derailment sites that were attributed to specific geometry exceptions/defects as defined in the existing track safety standards.
- Explore the potential relationship of derailment risk to each of the measures and associated thresholds adopted in the existing track standards and, where some relationship is found to exist, assess whether a model-based approach that highlights L/V conditions is an adequate replacement.
- Assess the incremental cost versus reduced derailment risk associated with adopting lower L/V thresholds and more stringent assumptions in the model.
- Assess the merits of adopting additional measures of performance beyond derailment risk in a track performance measure.

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